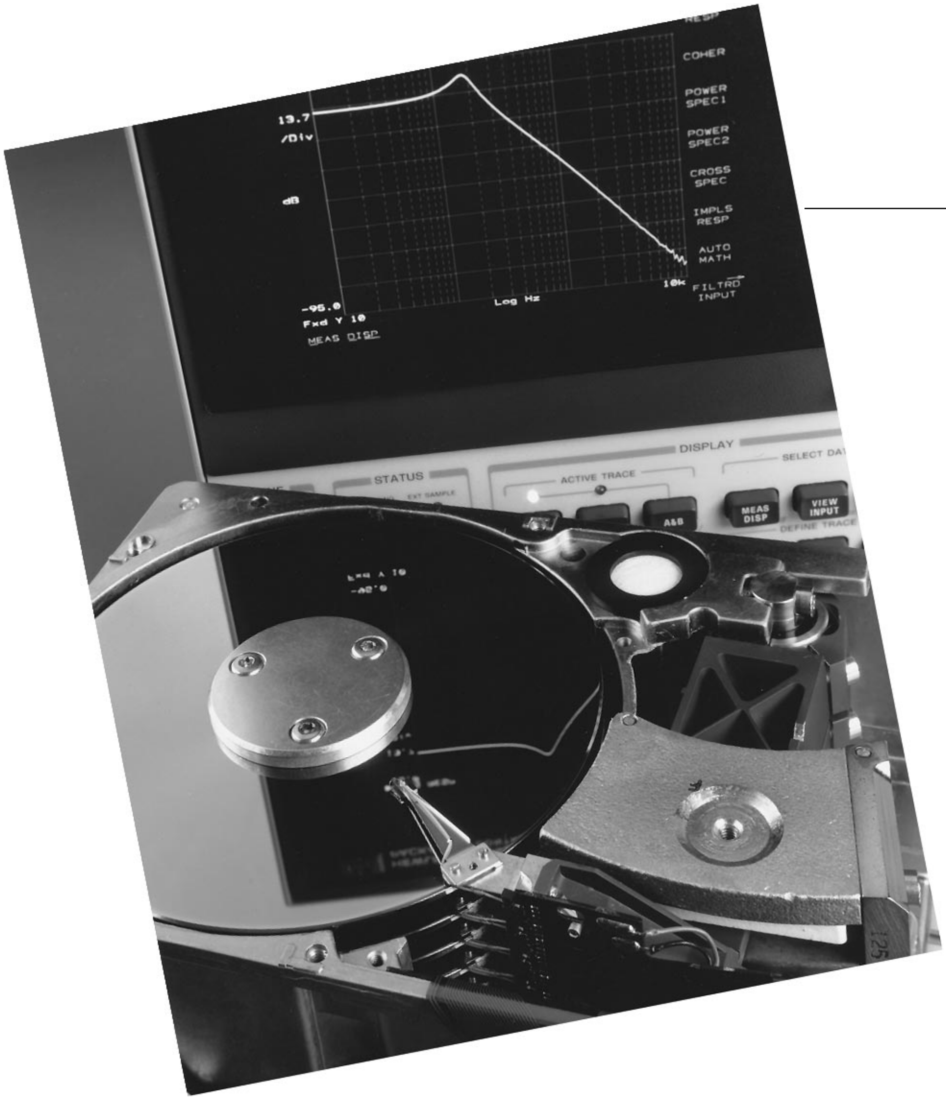
Bearing Runout Measurements

Application Note 243-7



Introduction

Advanced precision machinery, from centrifuges to computer disk drives, rely on precision bearing and spindle assemblies for high performance. For example, the spacing of data tracks on a computer disk drive can be limited by the non-repeatable runout of the spindle bearing assembly. For reasons like these, the need to measure runout and diagnose its cause has increased in recent years.

Traditionally, runout has been measured with the electronic equivalent of a dial indicator and oscilloscopes which can determine the magnitude of runout. More recently, spectrum analyzers have been used because they can help identify the various causes of runout by providing the frequency distribution information, as well as the data available from other testing methods. Originally confined to design labs, spectrum analyzers are now finding their way into incoming inspection and onto the manufacturing floor, where they are used to measure changes in runout caused by critical assembly steps.

This note explores the advantages of using a dynamic signal analyzer to make runout measurements, using both the traditional time domain measurements as well as spectrum measurements. The measurements shown were made on a disk memory spindle assembly.

Test setup to measure runout

Figure 1: Experimental runout test set up

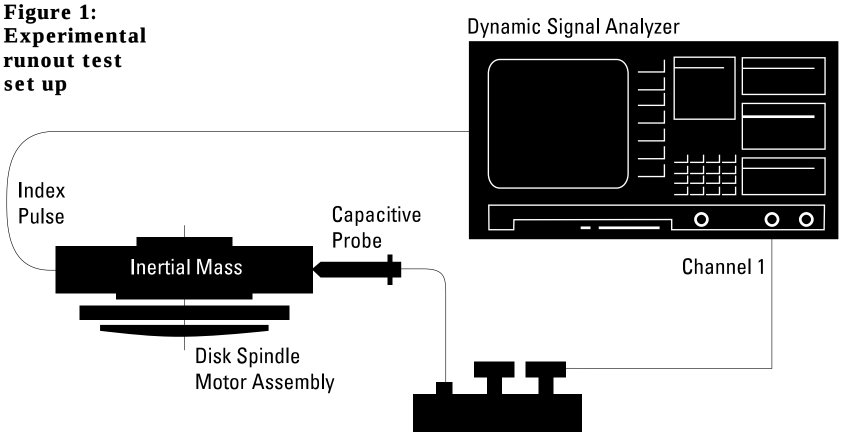
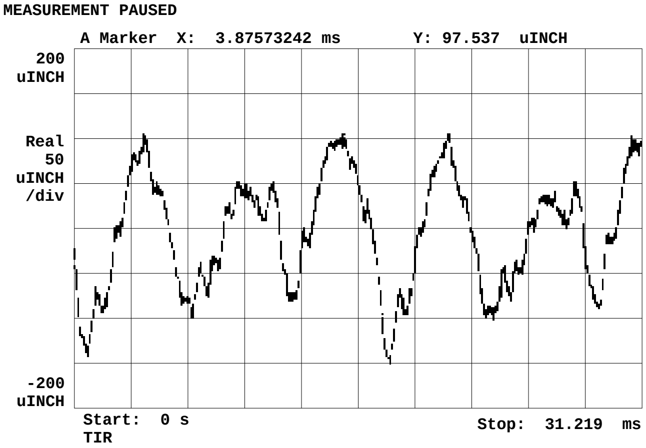


Figure 1 shows a typical test setup to measure spindle runout. The motor and spindle assembly is typically loaded with an inertial mass to simulate actual running loads. A proper load is often required for the spindle servo to maintain a constant speed.

The runout in this example is measured by placing a proximity probe close to the hub at the end of the spindle. The probe, with its electronics, produces a signal that is proportional to the air gap between the hub and the probe. This signal is fed into a dynamic signal analyzer, where it is digitized into an amplitude vs. time record.

A once-per-revolution tach pulse (INDEX) is needed from the spindle assembly to drive the external trigger input on the analyzer. This ensures that data collection starts at the same angle of rotation for each average.

Figure 2: Total indicated runout for two revolutions of the hub. The fuzziness indicates the non-repeatable runout.



Time domain measurements of repeatable and nonrepeatable runout

In the time domain mode, the analyzer shows Total Indicated Runout (TIR) as it changes with the revolution of the spindle. TIR has two components. Repeatable runout, the largest component (up to 2 mils in this case), is caused by the center of rotation being offset from the physical center of the part, as well as surface irregularities on the hub. The runout component of interest is the nonrepeatable part, which can be 1000 (60 dB) smaller than the repeatable runout. In precision machinery, NRR is caused largely by imperfections in the bearings.

Repeatable runout in the spindle assembly is not a great concern because it is the same for every revolution and can be compensated for. For example, a disk drive writes a servo track that is concentric with the center of rotation. The non-repeatable runout (NRR) can not be compensated for and therefore is the precision limit for the spindle bearing assembly. In the case of a computer disk drive, the goal is to maintain a peak-to-peak NRR less than 5% of the spacing between the tracks. In a disk with 1000 tracks-per-inch, a NRR of <20 microinches peak-to-peak is desirable.

Figure 2 shows a single TIR measurement made with a dynamic signal analyzer. Since the spindle speed is 60 Hz (3,600 RPM), the time period for each revolution is 16.7 milliseconds. The time record length shown in the figure is just over 31 milliseconds, thus showing almost two complete revolutions of runout.

Determining non-repeatable runout with Dynamic Signal Analyzers

NRR can be computed by subtracting repeatable runout from a single TIR measurement. The repeatable runout is measured by time averaging many TIR measurements together. The nonrepeatable parts of the TIR are averaged out. This method is more precise than drawing limit lines on an oscilloscope or eyeing peak-to-peak fuzziness of many TIR measurements superimposed on each other.

To determine the repeatable runout, time records used in the average must be synchronized; data collection for each time record must start at the same angular location on the spindle. To do this, an external trigger is used to start data collection for each time record at the same angle of rotation on the disk spindle. The average smooths out and converges on the repeatable runout (figure 3). For vector averaging to work properly, the speed of the spindle should be regulated within 1% or better[1].

Next, capture a new time record of TIR. Subtract the repeatable runout from the total runout. The difference is the NRR versus time. This subtraction removes all repeatable eccentricities and surface runout effects (figure 4).

The results of such testing are evaluated by looking for the peak-to-peak NRR. The one sigma variance or repeatability of the NRR versus time measurement is typically 20-50%.

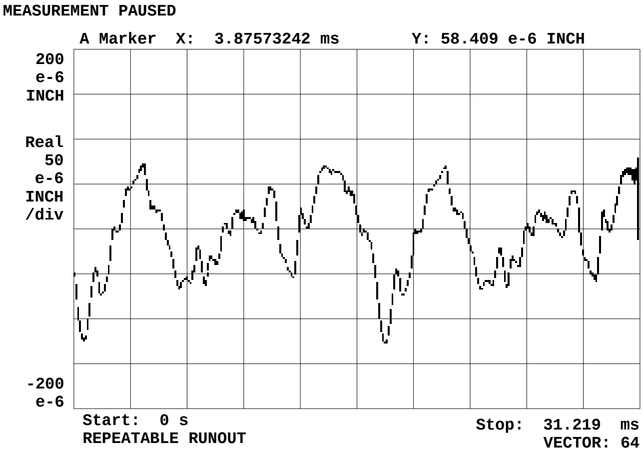


Figure 3: Repeatable runout is obtained by using Vector/Time Averaging to average out the non-repeatable contribution to runout.

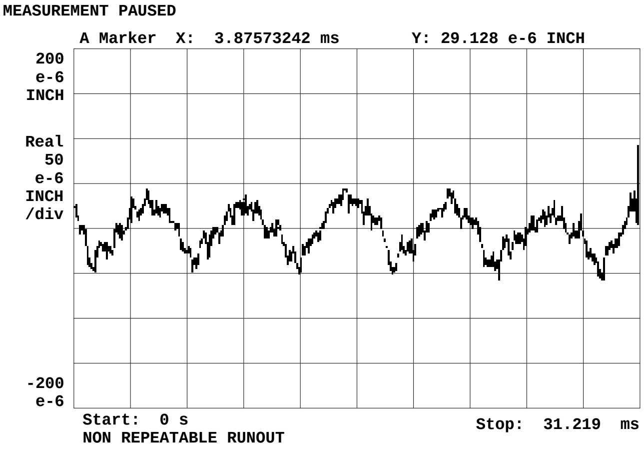


Figure 4: Non-repeatable runout is the difference between a TIR measurement and the repeatable runout.

Unfortunately, this time domain approach can not be used to diagnose the causes of NRR because the result is simply a display of amplitude versus time. A different measurement method is needed to break NRR into components that can be related to bearing defects.

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[1] Computed order tracking can handle conditions or speed regulation.

Frequency domain measurements of synchronous and asynchronous runout

The next step in runout testing is to use a spectrum analyzer to look at the different components of runout. When runout is displayed as amplitude versus frequency, the runout contributions from variations on the inner race, outer race, and rolling elements stand out as separate spectral components (figures 5 & 6). Variation analysis becomes more quantitative and less guesswork. This approach of measuring runout in the frequency domain is referred to as synchronous and asynchronous runout, differentiating it from the time domain measurements of repeatable runout and NRR.

Synchronous runout is the spectrum of the repeatable runout, which is the result of vector averaging many TIR measurements. Figure 5, the synchronous runout spectrum, contains runout components that are due to the hub eccentricity, hub finish and any other repeatable bearing runout. The off-synchronous runout components reduce in amplitude at a rate of $1\sqrt{k}$ where k is the number of averages. So 64 averages will attenuate the asynchronous contributions by a factor of eight.

Figure 6 shows a spectrum of total or average runout, measured by using standard rms averaging of spectra instead of using vector (time) averaging. Since rms averaging is a squared average, all the contributors to run out, synchronous and asynchronous, accumulate in the measurement.

Figure 5: Synchronous runout is measured by using Vector/Time Averaging. Note the markers set at 60 Hz and its harmonics.

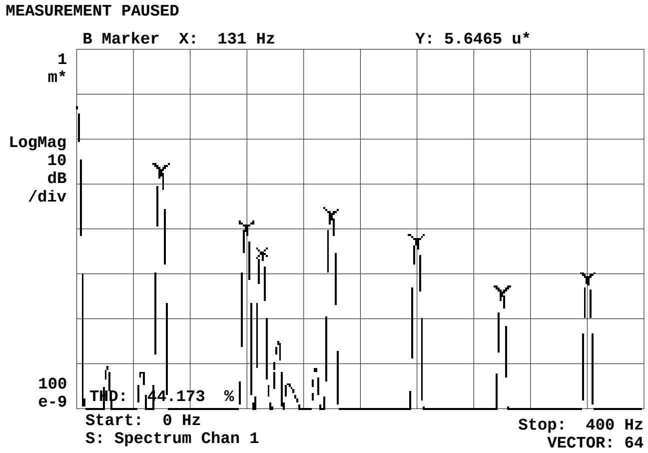


Figure 6: Total runout is measured using rms averaging. Notice the noise floor is higher and the amplitude of the 131 Hz component is greater, than adjacent harmonics of 60 Hz.

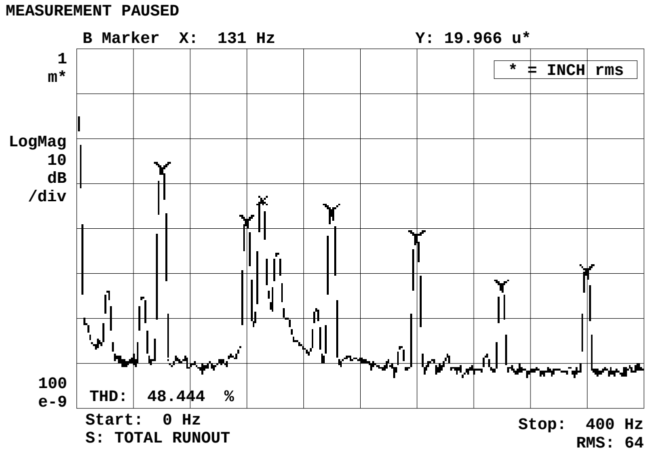


Table 1: Bearing Characteristic Frequencies

Defect on outer race (Ball pass frequency outer)	$= \frac{(n)}{2}\,\frac{(RPM)}{60}\left(1 - \frac{Bd}{Pd}\cos \text{ø}\right)$
Defect on inner race (Ball pass frequency outer)	$= \frac{(n)}{2}\,\frac{(RPM)}{60}\left(1 + \frac{Bd}{Pd}\cos \text{ø}\right)$
Ball defect (ball spin frequency) (Ball pass frequency outer)	$= \frac{(Pd)}{2Bd}\,\frac{(RPM)}{60}\left[1 - \left(\frac{Bd}{Pd}\right)^2 \cos^2 \text{ø}\right]$
Fundamental train frequency (Ball pass frequency outer)	$= \frac{(n)}{2}\,\frac{(RPM)}{60}\left(1 - \frac{Bd}{Pd}\cos \text{ø}\right)$

Pd = Pitch diameter
Bd = Ball diameter
n = Number of balls
ø = Contact angle

Note: for bearing spindle assemblies where the inner race is stationary, the bearing frequency can be calculated by changing the sign in the brackets or parentheses.

Interpreting the asynchronous measurement

Examining spectral components is the first step in analyzing runout. Both figures 5 and 6 are dominated by repeatable or synchronous runout at 60 Hz and harmonics (marked by harmonic markers). The off-rotational speed spectral lines are due to the runout of the bearing components i.e., the inner and outer race ballpass and the ball train and ball spin frequencies. These different frequencies can be computed with the equations in table 1. Because the balls slip a little rather than roll continuously, the predicted frequencies will be slightly higher than what is actually measured.

Asynchronous runout is computed by subtracting the synchronous runout, figure 5, from the total runout of figure 6. Since the runout in this example is determined from two averaged measurements with 3800 revolutions each, the repeatability of this asynchronous runout measurement is much better than with the time domain approach. The one-sigma variance in this case is less than 3%.

Figure 7 shows asynchronous runout that was computed by subtracting the synchronous runout (figure 5) from the rms runout (figure 6). The largest component of asynchronous runout is at 131 Hz. Analysis of the bearing design, using the equations in table 1, indicates this runout component occurs at the ball spin frequency of the bearing. This indicates the runout is caused by the out-of-roundness of the balls themselves.

It is also interesting to look at the markers which denote the harmonics of 60 Hz (the spindle speed). For the harmonics, the value of asynchronous runout is zero. However, at 60 Hz, there is a significant level of asynchronous runout. This is surprising because runout at the spindle speed is typically synchronous.

To investigate the cause of this unexpected component, a new measurement is made with a center frequency of 60 Hz and an increased resolution of 1/8 Hz. In figure 8, the 60 Hz component now shows up with sidebands spaced at 2.5 Hz. This indicates gyroscopic precession of the spindle assembly at a rate of

Figure 7: Asynchronous runout shows contributions at 131 Hz and 60 Hz.

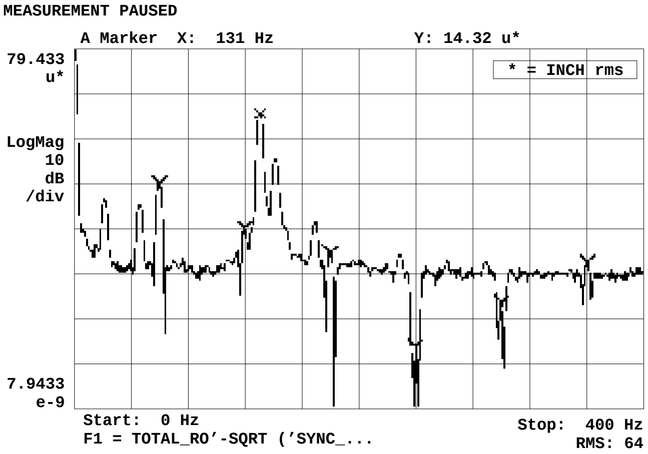
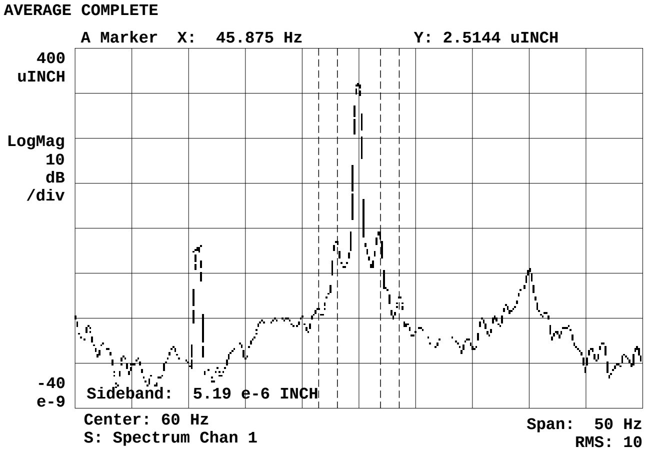


Figure 8: A zoom measurement at 60 Hz shows sidebands spaced 2.5 Hz, an indication of precession.



2.5 Hz. Precession is not synchronous with the spinning of the spindle, and is a common cause of asynchronous runout at the spindle speed.

Test Setup Considerations

The trigger signal from the shaft must be stable with fast rise time and occurs only once-per-revolution. An optical tach that provides a TTL logic level of less than .2 V to greater than +3.6 V is ideal. Magnetic tachs can be used if adequate signal shaping and signal conditioning are provided. The bearing fixtures and proximity probe mounting must be rigid and also micrometer adjustable so the probe can be positioned for best performance.

Spindle bearing assemblies for computer disk drives now have NRRs of 10 microinches peak-to-peak or less. This presents a measurement problem because the noise performance of proximity probes used for the measurements has lagged the industry needs. Noise values of 6 to 20 microinches are common on commercially available proximity probes, which means transducer noise can easily dominate the results of a runout measurement on a high precision bearing. When selecting a proximity probe for measurements on precision machinery, be certain to get one with low noise and high sensitivity.

It is important to have adequate dynamic range in the analyzer because the asynchronous runout is a very small difference between two large values. If the peak-to-peak value of NRR is 10 microinches on a 1 mil peak-to-peak TIR, then the analyzer should have a dynamic range of greater than 60 dB (1000 to 1) to insure an uncertainty of less than 10% in the 10 microinch measurement. Typically, an analyzer with >72 dB of true dynamic range (>13 bit A-D converters) is required to insure accurate repeatable measurements of runout. To maximize the useful dynamic range of the analyzer, it is important to think about the dc value in the spectrum. If the electronics for the proximity probe have a dc bias, the input to the analyzer should be ac coupled.

Correlation between the Two Measurement Techniques

The correlation between the time domain NRR measurement and the asynchronous runout measurement can be as good as .98, which indicates that frequency domain measurements can be used to accurately quantify runout. Consistently high correlations between time domain NRR and frequency domain asynchronous runout measurements can not be expected because the variance of time domain NRR can be as much as 50%. In comparison, variance of asynchronous runout measurements can be on the order of 5% because so many averages are used in making a measurement.

Conclusion

Spectrum measurements of asynchronous runout offer insight into bearing analysis that is not available with time domain NRR measurements. By breaking up runout into different spectral components, it becomes possible to relate runout to specific bearing defects. This analysis capability is valuable in the design lab to determine performance limitations, and also on the manufacturing floor for statistical quality control.

Spectral analysis of bearing runout is an ideal bearing condition monitoring tool. Bearing wear is directly measured as opposed to inferring it from an acceleration measurement. Spectral analysis will identify other rotational degrees of freedom such as gyroscopic precession which would be impossible with time domain NRRD measurements.

Appendix A

Procedure for measuring non-repeatable runout

Step 1: Measure repeatable runout by setting the analyzer to the following measurement state:

Measurement Data:	Time Channel 1 [†]
Record Length	31.25 ms
Window	Uniform
Average Status	On
Average Type	Time
Number of Averages	64
Trigger	External

When the measurement is complete, save the result in the first data register (D1).

Step 2: Capture a TIR measurement by setting the analyzer to the following measurement state:

Measurement Data:	Time Channel 1
Record Length	31.25 ms
Window	Uniform
Average Status	On
Average Type	RMS
Number of Averages	1
Trigger	External

When the measurement is complete, save the result in the second data register (D2).

Step 3: Compute Non-Repeatable Runout

Create the following Math function:

F2 = D2 - D1 [††]

For a continuous updated display of NRRO, change D2 to Time 1, and set average status to off.

Appendix B

Procedure for measuring asynchronous runout

Step 1: Measure synchronous runout by setting the analyzer to the following measurement state:

Measurement Data:	Linear Spectrum1
Window	Flat Top
Average Status	On
Average Type	Vector
Number of Averages	64
Trigger	External

When the measurement is complete, save the result in the first data register (D1).

Step 2: Measure the total runout spectrum by setting the analyzer to the following measurement state:

Measurement Data:	Power Spectrum 1
Window	Flat Top
Average Status	On
Average Type	RMS with 50% overlap
Number of Averages	64
Trigger	Free Run

When the measurement is complete, save the result in the third data register (D3).

Step 3: Compute Asynchronous Runout

Create the following Math function:

F3 = D3 - SQRT (D1 * CONJ (D1))[†††]

For a continuous updated display of asynchronous runout, substitute PSPEC for D3 and set average status to off.

References

HP Application Note 243-1 Effective Machinery Maintenance Using Vibration Analysis (P/N 5962-7276E)

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[†] **Note about time averaged measurements: The analyzer does not average time records. Time averaging averages linear spectra. The averaged time record is obtained by taking the inverse FFT of a linear spectrum. If your analyzer does not provide time averaging, specify a linear spectrum and vector averaging. Save the results in the first data register, D1. To display the repeatable runout, create the following math function:**

Function 1 = IFFT (LSPEC1)

[††] **Note: If you specified vector averaging and a linear spectrum in Step 1, create the following Math function:**

F2 = D2 - IFFT(D1)

[†††] **Note about time averaging: During time averaging, a linear spectrum is saved. It is a complex valued function with real and imaginary values for each frequency. During RMS averaging, a power spectrum is saved. It is a magnitude only function with real values only. The synchronous spectrum, which is a linear spectrum, must be converted to a power spectrum before it can be subtracted from the RMS averaged spectrum. The math function described above computes the power spectrum of D1 before subtracting it from D3.**

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